CHAPTER 5

CPR Baseline Appropriation Experiments

As discussed in chapter 1, the problems that appropriators face can be usefully clustered into two broad types: *appropriation* and *provision*. In appropriation problems, the production relationship between yield and level of inputs is assumed to be given and the problem to be solved is how to allocate that yield in an efficient and equitable manner. Provision problems, on the other hand, are related to creating a resource, maintaining or improving the production capabilities of the resource, or avoiding the destruction of the resource. In other words, in appropriation problems, we focus attention on the *flow* aspect of the CPR. In provision problems, we concentrate on the *facility* aspect of the CPR.

Both appropriation and provision problems are found in most CPR settings. In fact, in most field settings, these problems are nested in complex interrelationships that are clearly interdependent. A laboratory setting, however, allows the analytical separation of such interdependencies. To date, our experimental work has focused principally on (1) issues related to appropriation in a static environment or (2) appropriation and its relation to demand-side provision, the impact of appropriation in a dynamic sense on resource yield and on probabilistic destruction of the CPR. We have analyzed these issues in decision settings with very basic rule configurations and in settings in which rules were altered to examine how institutional changes affect appropriation decisions. Although the experimental research conducted for this book does not explicitly examine the supply-side provision or maintenance problems faced by CPR users, there is substantial experimental research closely related to this issue. We include a brief summary of this research as appendix 5.1 to this chapter.

CPR Appropriation

We now turn to our most basic appropriation setting. The first question that we need to pursue in the laboratory setting is whether subjects' decisions in a stark CPR dilemma situation are similar to those predicted by noncooperative game theory. In other words, would subjects presented with a CPR dilemma, similar to the appropriation game of chapter 3, appropriate from the laboratory CPR as predicted by the Nash equilibrium? This is our baseline game. These experiments represent a baseline in the sense that we examine behavior in a situation with minimal institutional constraints. The purpose of such experiments is twofold: (1) it allows for a close examination of individual and group behavior under conditions designed to parallel those of noncooperative complete information game theory and (2) it provides a benchmark for comparison to behavior under alternative physical and institutional configurations. Our baseline situation is designed to analyze appropriation behavior in a time-independent (stationary) condition.[1] Thus, this situation allows us to investigate appropriation behavior separate from provision behavior. The baseline situation clearly avoids the "real world" phenomena that the productive capacity and possible destruction of CPRs is dependent upon the level of appropriation from the CPR or that in some CPRs institutions have evolved in an attempt to diminish the effects of resource degradation. In the three chapters following this "baseline" chapter, we examine laboratory situations that allow for the probabilistic destruction of the CPR and institutions designed to allow communication and/or sanctioning.

Appropriation Behavior in the Laboratory

Subjects and the Experimental Setting

The experiments used subjects drawn from the undergraduate population at Indiana University. Students were volunteers recruited primarily from principles of economics classes. Prior to recruitment, potential volunteers were given a brief explanation in which they were told only that they would be making decisions in an "economic choice situation" and that the money they earned would be dependent upon their own investment decisions and those of the others in their experimental group. All experiments were conducted on the NovaNET computer system at Indiana University. The computer facilitates the accounting procedures involved in the experiment, enhances across experimental/subject control, and allows for minimal experimenter involvement.

At the beginning of each experimental session, subjects were told that (1) they would make a series of investment decisions, (2) all individual investment decisions were anonymous to the group, and (3) they would be paid their individual earnings (privately and in cash) at the end of the experiment. Subjects then proceeded at their own pace through a set of instructions that described the decisions.[2]

Subjects were instructed that in each decision round they would be

1. This chapter relies extensively on J. Walker, Gardner, and Ostrom 1990.
2. A complete set of instructions is available from the authors upon request.

Tokens Invested by Group	Units of Commodity Produced	Total Group Return	Average Return per Token	Additional Return per Token
20	360	$ 3.60	$ 0.18	$ 0.18
40	520	$ 5.20	$ 0.13	$ 0.08
60	480	$ 4.80	$ 0.08	$ -0.02
80	240	$ 2.40	$ 0.03	$ -0.12
100	-200	$ -2.00	$ -0.02	$ -0.22
120	-840	$ -8.40	$ -0.07	$ -0.32
140	-1680	$ -16.80	$ -0.12	$ -0.42
160	-2720	$ -27.20	$ -0.17	$ -0.52
180	-3960	$ -39.60	$ -0.22	$ -0.62
200	-5400	$ -54.00	$ -0.27	$ -0.72

Note: The table displays information on investments in Market 2 at various levels of group investment. Your return from Market 2 depends on what percentage of the total group investment is made by you.

Market 1 returns you one unit of commodity 1 for each token you invest in Market 1. Each unit of commodity 1 pays you $ 0.05.

Fig. 5.1. Table presented to subjects showing units produced and cash return from investments in Market 2 (commodity 2 value per unit = $ 0.01)

endowed with a given number of tokens that they could invest in two markets. Market 1 was described as an investment opportunity in which each token yielded a fixed (constant) rate of output and each unit of output yielded a fixed (constant) return. Market 2 (the CPR) was described as a market that yielded a rate of output per token dependent upon the total number of tokens invested by the entire group. The rate of output at each level of group investment was described in functional form as well as tabular form. Subjects were informed that they would receive a level of output from Market 2 that was equivalent to the percentage of total group tokens they invested. Further, subjects knew that each unit of output from Market 2 yielded a fixed (constant) rate of return. Figure 5.1 displays the actual information subjects saw as summary information in the experiment. Subjects knew with certainty the total number of decision makers in the group, total group tokens, and that endowments were identical. They knew that the experiment would not last more than two hours. They did not know the exact number of investment decision rounds. All subjects were *experienced*, that is, had participated in at least one experiment using this form of decision situation.[3]

3. Subjects were randomly recruited from initial runs to ensure that no group was brought back in tact. The number of rounds in the initial experiments varied from 10 to 20.

In the baseline experiments, eight subjects participated in a series of at least 20 decision rounds. After each round, subjects were shown a display that recorded: (1) their profits in each market for that round, (2) total group investment in Market 2, and (3) a tally of their cumulative profits for the experiment. During the experiment, subjects could request, through the computer, this information for all previous rounds. Players received no information regarding other subjects' *individual* investment decisions or concerning the number of iterations.

Note that this laboratory decision situation parallels that of an action situation described in chapter 2. A careful experimental investigation requires that each of the seven components of an action situation be clearly defined. Thus, the baseline action situation we have created in the lab has the following components of an action situation: (1) eight participants; (2) all participants hold the same position; (3) participants must make a token allocation for an experimentally controlled number of decision rounds; (4) output is in terms of units of production for Markets 1 and 2; (5) a deterministic function maps aggregate investments in Markets 1 and 2 into the number of units produced in Markets 1 and 2; (6) participants know the number of other players, their own endowment, their own past actions, the aggregate past actions of others, the payoff per unit for output produced in both markets, the allocation rule for sharing Market 2 output, the finite nature of the game's repetitions; and (7) participants know the mapping from investment decisions into net payoffs.

We interpret our baseline laboratory CPR situation in the following manner. It is limited access in the sense that an upper limit of eight players invests a maximum number of tokens in the CPR (Market 2). While this decision situation has a limited number of players, players in combination have sufficient freedom to choose investment levels that lead to extremely suboptimal yields. In fact, we examine the behavioral consequences of varying the endowments available to appropriators (the number of tokens) from 10 to 25 tokens per person per round. Although eight may be a small number of players, our baseline design approximates some of the characteristics of larger groups or conflict-ridden small groups because it does not allow explicit communication. In this baseline experiment, it is difficult for individuals to signal one another about their intentions. Information about the actions by one player is swamped by the actions of others, since players only receive information on aggregate group investment decisions and outcomes.

Further, our laboratory CPR brings together, for a relatively short period of time, players who have no relevant prior history that might implicitly enable them to coordinate behavior. The participants know the experiment will last no more than two hours and that all decisions remain anonymous to

other participants.[4] Thus, while the participants do not know the specific number of rounds, they know the experiment has a relatively short finite horizon. The experimental situation has been consciously neutralized in the sense that players are not explicitly given clues to (1) what we expect of them or (2) naturally occurring parallel decision environments (e.g., we don't call them fishers or Market 2 a fishery). Finally, we emphasize again, that our baseline situation separates appropriation activity from provision. The resource is provided by the experimenters. Endowments, the production functions, the payoff functions, and the number of decision rounds are not dependent upon decisions made in any round.

Theoretical Predictions about Individual Behavior in the Baseline Experiment

Assume a fixed number n of appropriators with access to the CPR. Each appropriator i has an endowment of resources e that can be invested in the CPR or invested in a safe, outside activity. The marginal payoff of the outside activity is normalized equal to w, measured in cents. The payoff to an individual appropriator from investing in the CPR depends on aggregate group investment in the CPR, and on the appropriator investment as a percentage of the aggregate. Let x_i denote appropriator i's investment in the CPR, where $0 \leq x_i \leq e$. The group return to investment in the CPR is given by the production function $F(\Sigma x_i)$, where F is a concave function, with $F(0) = 0$, $F'(0) > w$, and $F'(ne) < 0$. Initially, investment in the CPR pays better than the opportunity cost of the foregone safe investment $[F'(0) > w]$, but if the appropriators invest a sufficiently large number of resources ($\hat{q}$) in the CPR, the outcome is counterproductive $[F'(\hat{q}) < 0]$. The yield from the CPR reaches a *maximum net level* when individuals invest some, but not all, of their endowments in the CPR.[5]

So far all CPR games we have considered had two players. This restriction was solely for purposes of exposition. Most real-world CPR problems involve many more participants. We let the parameter n represent the number of players in a CPR experimental game. For all the experiments reported in this book, n is set equal to eight. Even though many CPR problems involve more than eight participants, with eight participants one encounters most of

4. Contrast this finite game design with one illustrated by Palfrey and Rosenthal 1992, where a random stopping rule was used to create the theoretical equivalence of a discounted infinitely repeated game.

5. Investment in the CPR beyond the maximum net level is termed *rent dissipation* in the literature of resource economics. This is conceptually akin to, but not to be confused with, the term *rent seeking*, which plays an important role in political economy and public choice. For the latter, see Tullock 1967 and Krueger 1974.

the strategic complexity inherent with larger groups. Moreover, there is sound theoretical reason to believe that eight is a large enough number to surmount small-group effects.[6]

We now introduce some notation that will prove useful. Let $\boldsymbol{x} = (x_1, \ldots, x_n)$ be a vector of individual appropriators' investments in the CPR. The amount that individual i does not appropriate to the CPR, $e - x_i$, is automatically invested in the safe outside alternative. The vector notation $\boldsymbol{x}$ reminds us of the fact that the payoff to a participant depends in general on what all the participants do. The payoff to an appropriator, $u_i(\boldsymbol{x})$, is given by:

$$u_i(\boldsymbol{x}) = \begin{cases} we & \text{if } x_i = 0 \\ w(e - x_i) + (x_i/\Sigma x_i)F(\Sigma x_i) & \text{if } x_i > 0. \end{cases} \qquad (5.1)$$

What equation (5.1) says is really quite straightforward. If players put all their endowment into the safe alternative, they get the sure value (endowment)(value per unit of endowment) = $(e)(w)$. If players put some of their endowment into the safe alternative and some into the CPR, they get a return of $w(e - x_i)$ on that part of the endowment invested in the safe alternative. In addition, they get a return from the CPR, which equals their proportional investment in the CPR, $(x_i/\Sigma x_i)$, times total CPR output $F(\Sigma x_i)$, measured in cents.

More players in a game means more complexity. However, the basic concepts of payoff maximization and Nash equilibrium remain the same. In particular, at a Nash equilibrium, each player maximizes payoff given the strategies chosen by the other players. Let x_i be player i's strategy and $u_i(x)$ be player i's payoff function, in a general formulation of which (5.1) is a particular instance. Player i seeks to maximize her payoff by her choice of x_i, which itself is a constrained variable. When the payoff function is differentiable, as is (5.1), this maximization can be performed using calculus techniques. Consider the calculus problem:

$$\underset{x_i}{\text{maximize}}\ u_i(\boldsymbol{x})$$

$$\text{subject to } 0 \leq x_i \leq e.$$

6. In an influential paper, Selten (1971) argues that five is the crucial number of players. In an oligopoly game similar to ours, he shows that with fewer than five players, the most likely equilibrium (without institutional innovation) involves considerable amounts of cooperation, while with more than five players, an effect reminiscent of a CPR problem is present at equilibrium.

Suppose that x_i^* solves the constrained maximization problem, and that $u_i(x_1, \ldots x_i^*, \ldots x_n)$ is the maximal value. This gives one equation in n unknowns. Now solve the calculus problem for each player i. Then one has n equations in n unknowns. Any solution to this system of equations is a Nash equilibrium. In other words, a Nash equilibrium requires that all n players have solved their individual maximization problems simultaneously. That is, suppose that for each player i, x_i^* is the solution to the individual maximization problem. Then at a Nash equilibrium, the problem that player i faces (if every other player is maximizing—is playing the optimal x_i^*) is

$$\underset{x_i}{\text{maximize}}\ u_i(x_1^*, \ldots x_i, \ldots x_n^*)$$

$$\text{subject to } 0 \leq x_i \leq e$$

is solved by x_i^*. Since there is a first-order condition for each player, solving for a Nash equilibrium in general requires that one solve n simultaneous equations in n unknowns. Computationally, solving this system can be quite challenging, which is one reason why games with many players are harder to analyze.

However, if the game is symmetric, there is a shortcut to the solution. Our baseline game is symmetric. Each player has the same endowment, the same set of pure strategies (and hence mixed strategies), and the same payoff function in cents. Under these conditions, the game is symmetric. Every symmetric game has a symmetric equilibrium. When a symmetric game has a unique symmetric equilibrium, Harsanyi-Selten selection theory selects that equilibrium.[7] To find this equilibrium, it suffices to solve a single player's maximization problem, together with the restriction that each x_i^* will be equal at equilibrium.

We illustrate this technique with the payoff function (5.1). Given our assumptions on the CPR production technology, it is easy to see that neither $x_i = 0$ nor $x_i = e$ solve player i's maximization problem. Therefore, there must exist an interior solution, where the first-order condition is satisfied. Differentiating (5.1), one has:

$$-w + (x_i/\Sigma x_i)F'(\Sigma x_i) + F(\Sigma x_i)((\Sigma x_i - x_i)/(\Sigma x_i)^2) = 0. \qquad (5.2)$$

7. As Claudia Keser pointed out, the baseline game also has asymmetric equilibria where one player invests 7 tokens, six players invest 8 tokens, and one player invests 9 tokens. The group investment is 64 tokens, the same as the symmetric equilibrium.

Symmetry implies that at equilibrium, each player makes the same investment decision as does player i. Invoking symmetry, one has $\Sigma x_i = nx_i^*$. Substitution into equation (5.2) yields

$$-w + (1/n)F'(nx_i^*) + F(nx_i^*)((n - 1)/x_i^*n^2) = 0.$$

As we show below, aggregate investment in the CPR at the symmetric Nash equilibrium is greater than optimal investment, and group return is less than optimal return, but not all yield from the CPR is wasted.[8]

There are several standard interpretations of this symmetric Nash equilibrium. First, it is the only solution to the maximization problem facing a rational player. Second, if a player does not obey (5.2), their payoff will be suboptimal. Third, once a player reaches this equilibrium, they have no incentive to change their behavior. Fourth, if one believes that strategic behavior is adaptive over long periods of time, then evolutionary forces (mimicking natural selection) will converge to an equilibrium satisfying (5.2).[9] A final interpretation is as the predicted outcome from a limited access CPR (see, for example, Clark 1980; Cornes and Sandler 1986; Hartwick 1982; and Negri 1989).[10] This is the interpretation most relevant for policy purposes.

We now compare the equilibrium to the optimal solution to the CPR problem. Summing across individual payoffs $u_i(\boldsymbol{x})$ for all appropriators i, one has the group payoff function $u(\boldsymbol{x})$,

$$u(\boldsymbol{x}) = nwe - w\Sigma x_i + F(\Sigma x_i) \tag{5.3}$$

which is to be maximized subject to the constraint $0 \leq \Sigma x_i \leq ne$. Given the above productivity conditions on F, the group maximization problem has a unique solution characterized by the condition:

$$-w + F'(\Sigma x_i) = 0. \tag{5.4}$$

According to (5.4), the marginal return from a CPR should equal the opportunity cost of the outside alternative for the last unit invested in the CPR. The

8. See J. Walker, Gardner, and Ostrom 1991 for details of this derivation.

9. In the terminology of evolutionary game theory, this equilibrium is an evolutionarily stable strategy. See Hofbauer and Sigmund 1988 for a mathematical survey of this fascinating subject.

10. Consistent Conjectural Variations Equilibria may provide a useful method for a detailed analysis of individual subject behavior in these experiments. In the limited access version of the noncooperative CPR decision problem, full dissipation is predicted by nonzero consistent conjectures. See Mason, Sandler, and Cornes 1988 for a discussion of consistent conjectures equilibria for the CPR experiment. See J. Walker, Gardner, and Ostrom 1991 for a discussion of several alternative theories that could be used to provide a solution to the constituent game.

group payoff from using the marginal revenue equals marginal cost rule (5.4) represents the maximal yield that can be extracted from the resource in a single period. Since equations (5.4) and (5.2) have different solutions, we have shown that the equilibrium is not an optimum.[11]

Neither the Nash equilibrium investment nor the optimum group investment depend on the endowment parameter e, as long as e is sufficiently large. For the Nash equilibrium this seems especially counterintuitive, since large values of e represent high potential pressure on the CPR. Strategically, one of the most problematic aspects of a CPR dilemma is overappropriation fueled by high endowments. Big mistakes are more likely and more devastating with high endowments. The Nash equilibrium concept fails to capture this, once the corner constraint that investment not exceed endowment is no longer binding.[12]

Denote the baseline game by X and let X be played a finite number of times. Game-theoretical models do not always yield unique answers to how individuals will (or ought to) behave in repeated, social dilemma situations. Such games can have multiple equilibria, even if the one-shot game has a unique equilibrium. The number of equilibria grows with the number of repetitions. When there are finitely many repetitions, no equilibrium can sustain an optimal solution, although it may be possible to come close (Benoit and Krishna 1985). When there are infinitely many repetitions, some equilibria can sustain an optimal solution (J. Friedman 1990). In all cases, the worst possible one-shot equilibrium, repeated as often as possible, remains an equilibrium outcome. The players thus face a plethora of equilibria. Without a mechanism for selection among these equilibria, the players can easily be overwhelmed by complexity and confusion.

A commonly used equilibrium selection criterion is to require that a strategy specify equilibrium play on subgames, the requirement of subgame perfection. If the baseline game has a unique symmetric equilibrium, then the finitely repeated game has a unique symmetric subgame perfect equilibrium (Selten 1971). Thus, equation (5.2) characterizes a finite sequence of equilibrium outcomes. We get symmetry among players within a decision period, as well as symmetry between decision periods.

This prediction, like all predictions made in this chapter, is based on the assumptions of a finite game and of complete information. Our experimental procedures assure that subjects know the game is finite.[13] Although we do not

11. Given the extent of market failure present in CPR dilemmas, this conclusion should come as no surprise to economists.

12. Interestingly enough, this criticism does not apply with the same force to cooperative versions of the baseline game.

13. During recruitment, subjects are told they will participate in a one-to-two-hour decision-making experiment. Although the exact endpoint is not revealed, it is explicitly bounded

have complete control over our subjects' understanding of their decision task, the information we make available fulfills the requirements for complete information. We try to ensure complete information on the part of our subjects by reporting results from experiments using only subjects experienced in the baseline game. Given our instruction and question-and-answer phases, we are confident that subjects actually understand the laboratory situations they face. In the unfortunate event that they do not, then there is a bewildering multiplicity of game equilibria from which to select, one of which remains the subgame perfect equilibrium (Kreps et al. 1982).

Experimental Design

In our experimental investigation, we have operationalized this CPR situation with eight appropriators ($n = 8$) and quadratic production functions $F(\Sigma x_i)$, where:

$$F(\Sigma x_i) = a\Sigma x_i - b(\Sigma x_i)^2$$

$$\text{with } F'(0) = a > w \text{ and } F'(ne) = a - 2bne < 0. \tag{5.5}$$

For this quadratic specification, one has from (5.4) that the group optimal investment satisfies $\Sigma x_i = (a - w)/2b$. The CPR yields 0 percent on net when investment is twice as large as optimal, $\Sigma x_i = (a - w)/b$. Finally, from (5.2), the symmetric Nash equilibrium group investment is given by:

$$\Sigma x_i = (n/(n + 1))(a - w)/b. \tag{5.6}$$

This level of investment is between maximal net yield and zero net yield, approaching the latter as n gets large. One additional constraint that arises in a laboratory setting is that the x_i be integer valued. This is accomplished by choosing the parameters a, b, n, and w in such a way that the predictions associated with Σx_i are all integer valued.

In particular, we focus on experiments utilizing the parameters shown in table 5.1. These parameters lead to the predictions portrayed in figure 5.2. A group investment of 36 tokens yields the optimal level of investment. This symmetric game has a unique symmetric equilibrium with each subject investing 8 tokens in Market 2.

above. Further, all subjects are experienced and have thus experienced the boundedness of an experiment that lasted between 10 and 30 rounds. In more recent experiments (Hackett, Schlager, and Walker 1993), the end point is public information. The behavior in these experiments closely parallels the behavior in experiments reported in this chapter.

TABLE 5.1. Parameters for a Given Decision Round, Experimental Design Baseline

	Type of Experiment	
	Low Endowment	High Endowment
Number of subjects	8	8
Individual token endowment	10	25
Production function[a]	$23(\Sigma x_i) - .25(\Sigma x_i)^2$	$23(\Sigma x_i) - .25(\Sigma x_i)^2$
Market 2 return/unit of output	\$.01	\$.01
Market 1 return/unit of output	\$.05	\$.05
Earnings/subject at group maximum[b]	\$.91	\$.83
Earnings/subject at Nash equilibrium	\$.66	\$.70
Earnings/subject at zero rent	\$.50	\$.63

[a]The production function shows the number of units of output produced in Market 2 for each level of tokens invested in Market 2. Σx_i equals the total number of tokens invested by the group in Market 2.
[b]Amounts shown are potential cash payoffs. In the high-endowment design, subjects were paid in cash one-half of their computer earnings.

Much of our discussion of experimental results will focus on what we term *maximum net yield* from the CPR. This measure captures the degree of optimal yield earned from the CPR. Specifically, net yield is the return from Market 2 minus the opportunity costs of tokens invested in Market 2, divided by the return from Market 2 at the investment level where marginal revenue equals marginal cost minus the opportunity costs of tokens invested in Market 2.[14] In our decision situation, opportunity costs equal the potential return that could have been earned by investing the tokens in Market 1. Note that for a given level of investment in the CPR, net yield is invariant with respect to the level of subjects' endowments.[15] Recall that even though the range for subject investment decisions is increased with an increase in subjects' endowments, the equilibrium and optimal levels of investment are not altered. At the Nash equilibrium, subjects earn approximately 39 percent of maximum net yield from the CPR.

Experimental Results

The baseline results from six experiments (three with 10-token endowments [experiments 1–3] and three with 25-token endowments [experiments 4–6])

14. In economics, this is the classical concept of rent.

15. An alternative measurement of performance would be to calculate overall experimental efficiency (actual earnings as a percentage of maximum possible earnings for the group). In our specific decision situation, this measurement has the undesirable property that it depends on subjects' token endowments. Our use of net yield, by avoiding endowment effects, gives a more accurate measure of the effect of behavior on CPR performance, our primary interest.

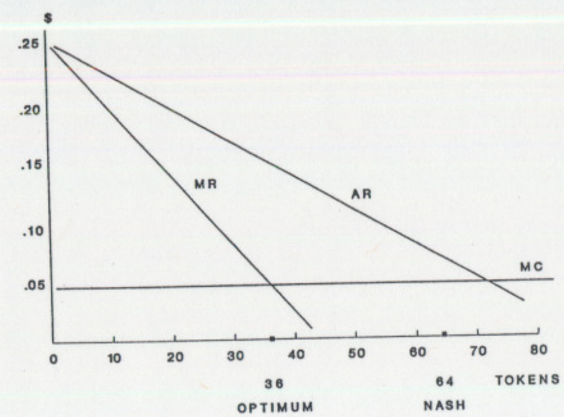

Fig. 5.2. Theoretical predictions (MR = marginal revenue, AR = average revenue, MC = marginal cost)

are summarized in table 5.2 and figure 5.3.[16] Appendix 5.3 contains round-by-round Market 2 investment decisions for all six baseline experiments. Table 5.2 displays information regarding net yield actually earned by subject groups. The most striking observation comes from increasing token endowments from 10 to 25. Aggregating across all experimental decision rounds, the average level of yields accrued in the low-endowment (10-token) design equalled 37 percent. In contrast, the average level for the high-endowment (25-token) design equalled −3 percent. From table 5.2, we see that it is in the early experimental rounds that the high-endowment treatment has its primary impact. In early rounds, a significant number of subjects make high investments in Market 2 leading to net payoffs that are as low as 382 percent below optimum. As the experiment progresses, the degree of suboptimality approaches that found in the low-endowment condition. The average tendencies for the first 20 decision rounds of the six experiments are presented in figure 5.4.

Several characteristics of the individual experiments are important. Investments in Market 2 are characterized by a "pulsing" pattern in which investments are increased leading to a reduction in yield, at which time

16. For clarity, the experiments in chapters 5–8 are numbered consecutively. Appendix 5.2 displays the book number for each experiment and the corresponding actual experiment number from our set of over one hundred experiments conducted in this research program.

TABLE 5.2. Average Net Yield as a Percentage of Maximum in Baseline Designs

	Round					
Experimental Design	1–5	6–10	11–15	16–20	21–25	26+
10-token (experiments 1–3)	52	35	34	36	37	30
25-token (experiments 4–6)	−43	−12	10	32	—	—

investors tend to reduce their investments in Market 2 and yields increase. This pattern tends to recur across decision rounds within an experiment. We did not find, however, symmetry across experiments in the amplitude or timing of peaks. For the high-endowment experiments, the low points in the pulsing pattern were at yields far below 0. Over the course of the experiments, there was some tendency for the variance in yields to decrease. We saw no clear signs that the experiments were stabilizing. Further, we observed no experiments in which the pattern of *individual* investments in Market 2 stabilized at the one-shot Nash equilibrium.[17] This failure of individual data to conform to the Nash equilibrium is a behavioral result that we will see throughout the next four chapters.[18]

To what extent does our data conform to the individual predictions for the equilibrium for this situation? We investigate two broad research questions and several more specific questions.

> Question 1—To what extent do round-by-round observations meet the criteria of 64 tokens allocated to Market 2?
> Question 2—What is the frequency of rounds in which individual investments of 8 were made?

Below, we present frequency counts across experiments that describe the extent to which individual decisions match those predicted by equation (5.2), namely invest 8 tokens in the CPR. We break down these two broad questions into components. The numbers in parentheses following each component question are the percentage of observations consistent with each question in 10-token (respectively, 25-token) experiments.

> Question 1—To what extent do round-by-round observations meet the criteria of 64 tokens allocated to Market 2?

17. Since the unique subgame perfect equilibrium is a sequence of one-shot equilibria, this implies that behavior did not stabilize at the subgame perfect equilibrium either.

18. We have observed disequilibrium at the individual level in every one of the more than one hundred experiments reported in this book.

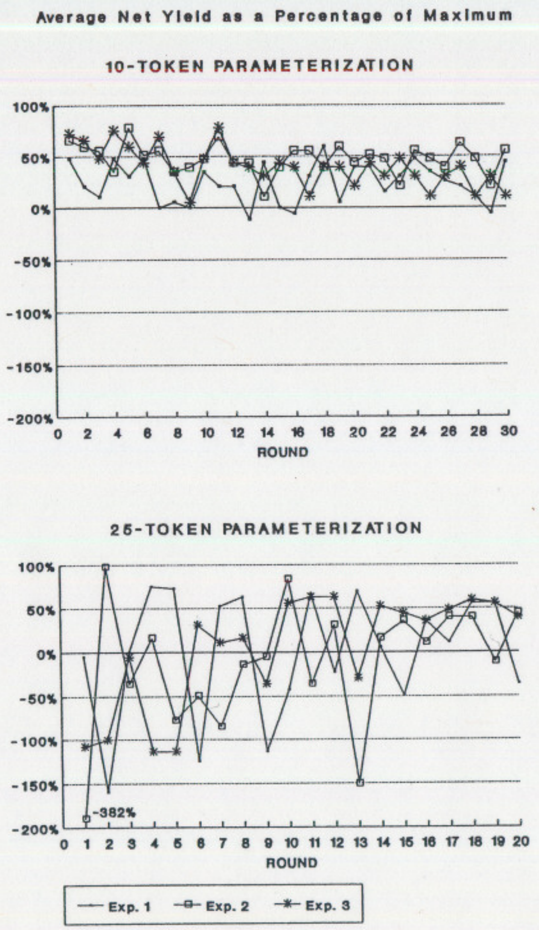

Fig. 5.3. Individual baseline experiments

(a) the number of rounds in which 64 tokens were allocated in Market 2 (11 percent, 5 percent).

(b) if 64 tokens were contributed to Market 2, the number of rounds in which all subjects invested 8 (0 percent, 0 percent).

Question 2—What is the frequency of rounds in which investments of 8 were made?

(a) rounds in which all investments were 8 (0 percent, 0 percent).

(b) rounds in which all but 1 investment was 8 (0 percent, 0 percent).

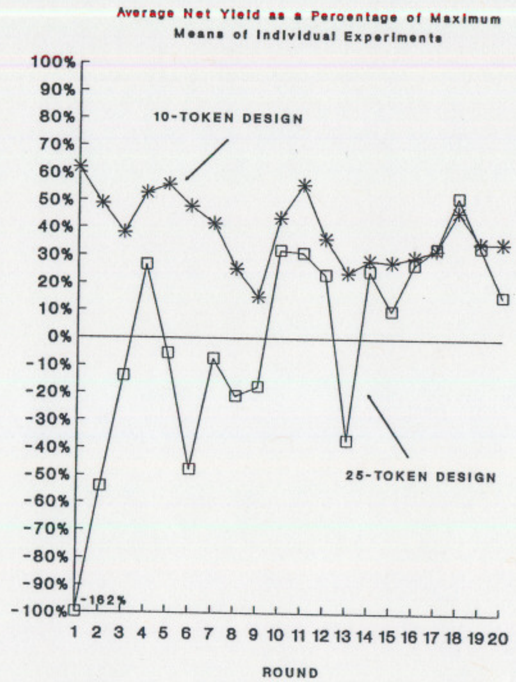

Fig. 5.4. The effect of increasing investment endowment

(c) rounds in which all but 2 investments were 8 (0 percent, 0 percent).

(d) rounds in which all but 3 investments were 8 (0 percent, 0 percent).

(e) rounds in which all but 4 investments were 8 (1 percent, 0 percent).

(f) rounds in which all but 5 investments were 8 (6 percent, 2 percent).

(g) rounds in which all but 6 investments were 8 (23 percent, 7 percent).

(h) rounds in which all but 7 investments were 8 (37 percent, 37 percent).

(i) rounds in which no investments of 8 were made (32 percent, 48 percent).

In summary, the data provide very little support for the research hypothesis that our investment environment will stabilize at the one-shot Nash equilibrium. Out of 90 investment rounds in the 10-token design, we find only 10 in which aggregate investment in Market 2 equals 64. In none of those 10 cases did we find a pattern of 8 tokens invested by each subject. Further, in all 90 investment rounds we find 4 or fewer of the 8 subjects investing the Nash equilibrium prediction of 8 tokens. In the 25-token design, we find even less support for the Nash prediction at the individual level. Of 60 investment rounds, we find only 3 in which Market 2 investment equals 64. In none of these 3 cases did all 8 investors invest 8 tokens. Further, aggregating across all 60 rounds, we find 5 or fewer individuals investing the Nash prediction of 8 tokens.

Turning to tables 5.3 and 5.4, we focus on individual strategies across rounds. Of the 24 subjects in the three 10-token experiments (table 5.3), no subject always played the strategy of investing 8 tokens in Market 2. Further, we found no subject consistently playing within one token of the Nash prediction (playing 9, 8, or 7). What happens if we analyze only the last 5 rounds of these 30-round experiments? In these final rounds, we find three subjects consistently playing within the one-token band around the Nash prediction. We also find 19 of 24 playing in the broader range of 6 to 10 tokens invested in Market 2. However, consistent with our previous designs, we find a strong pattern of players investing all 10 tokens in Market 2. In fact, in the final 5 rounds, 6 of the 24 players always invest 10 tokens. Table 5.4 provides similar information on individual behavior for our 25-token design. Similar to the 10-token design, we find very little support for the Nash prediction at the individual level. Further, our 25-token design clearly removes the allocation constraint we found in our 10-token design. No player always invested 25 tokens.

Conclusions

We can now address the first basic question posed in chapter 1: in finitely repeated CPR dilemmas, to what degree are the predictions about behavior and outcomes derived from noncooperative game theory for finitely repeated, complete information games supported by empirical evidence? Using experimental methods to control for subject incentives and to induce a set of institutional arrangements that capture the strategic essence of the appropriation dilemma, the results from this chapter strongly support the hypothesis of suboptimal appropriation. At the aggregate level, results initially appear to approximate a Nash equilibrium in a limited access CPR. But, instead of a pattern that settles down at the predicted equilibrium, we observe a general pattern across experiments where net yield decays toward 0 then rebounds as subjects reduce the level of investment in the common-pool resource. Investigating across two parameterizations, we find that at the aggregate level, our results lend strong support to the aggregate Nash equilibrium prediction for the low-endowment setting. In the high-endowment setting, however, aggregate behavior is far from Nash in early rounds but begins to approach Nash in later rounds. At the individual decision level, however, we do not find behavior consistent with the Nash prediction.

Several factors may contribute to the disequilibrium results we observe in these experiments. First and foremost is the computational complexity of the task. The payoff functions are nonlinear and nondifferentiable, making them difficult for our subjects to process. Indeed, in postexperiment questionnaires we administered, we found that many subjects were using the rule of thumb "Invest more in Market 2 whenever the rate of return is above $.05 per token." Then, when the rate of return fell below $.05, they reduced investments in Market 2, giving rise to the pulsing cycle in returns we observe across numerous experiments. A related factor is the focal point effect of investing 10 tokens in Market 2 (for our 10-token design), which is indeed the modal strategic response. Here, the rule of thumb seems to be "Invest *all* tokens in Market 2 whenever the rate of return there is above $.05 per token in previous decision rounds." This behavior is clearly inconsistent with full information, best-response behavior in these experiments. Finally, the fact that equilibrium is never reached at the individual level means that each player is continually having to revise his or her response to the current "anticipated" situation. This strategic turbulence on top of an already complex task increases the chances that a player may not attempt a best-response approach to

TABLE 5.3. Investment Patterns of Individuals, 10-Token Design

	Number of Individuals Always Investing						
	10	7–9	5–6	3–4	0–2	6–10	0–5
All rounds	3	0	0	0	0	9	0
Rounds 1–5	4	1	0	0	0	13	1
Rounds 26–30	6	3	1	0	0	19	1

TABLE 5.4. Investment Patterns of Individuals, 25-Token Design

	Number of Individuals Always Investing									
	25	7–9	5–6	3–4	0–2	21–25	16–20	11–15	6–10	0–5
All rounds	0	0	0	0	0	0	0	0	1	0
Rounds 1–5	0	1	0	0	0	0	0	0	1	1
Rounds 26–30	0	1	0	0	1	0	0	4	3	6

the task but rather invoke simple rules of thumb of the type reported above. In current work, Dudley (1993) has formally investigated the extent to which subjects appear to follow a reaction function consistent with Nash-type behavior.

The consistency with which we find deviations from Nash equilibrium is an important unanswered question posed by these results. It is a complex issue for experimental research in general. We know that for many institutional settings the Nash prediction can be quite robust. For example, in some of the public-goods provision situations discussed in the appendix to this chapter, there is considerable support for findings consistent with Nash. (Also see Cox, Smith, and Walker 1988 for the case of single-unit, sealed-bid auctions.) Even in this research, however, institutional changes, such as a change to multiple-unit auctions, can lead to subject behavior that is no longer consistent with a Nash model based on expected utility maximization (see Cox, Smith, and Walker 1984). Again, in duopoly experiments, Nash predictions for one-shot games are often borne out (Keser 1992 and the literature cited therein), although again predictive power seems to diminish with the number of players.

In the next four chapters, we extend the physical and institutional setting for our baseline game. In the next chapter, we explore the possibility of destruction of the CPR—a major concern in many naturally occurring CPR environments. One might hope that players would take the threat of the destruction of their resource seriously and would act accordingly—by reducing their investment pressure on it. In chapters 7–9, we explore the effect of communication and sanctioning institutions on these environments, while retaining noncooperative strategic interactions. We are interested in the possibility that, even without the ability to implement binding contracts, having a richer institutional environment leads to improved CPR performance.

APPENDIX 5.1. CPR PROVISION PROBLEMS

As discussed in chapter 1, provision and maintenance problems are linked conceptually to the general problem of public-goods provision. In situations where there must be an initial provision of the CPR, in the maintenance of a resource, or in altering appropriation behavior to affect the productive nature of a resource, users provide a public good (positive externality) to other appropriators.

To conduct an extensive examination of the experimental literature related to public-goods provision, however, is beyond the scope of this book. Even a cursory look forces one to realize this literature is broad and, as one might expect, the particular institutional design of a given experimental study is extremely important in understanding observed behavior. That is, the experimental literature points directly to the importance one must place on the institutional environment in which subjects carry out their decisions. In this brief summary, we summarize a few examples that illustrate the

importance of institutions, while giving an overview of the type of behavior observed in public-goods provision experiments.

One useful method for organizing public-goods experiments is to partition experiments along two treatment variables: (1) situations in which the Nash equilibrium yields no provision of the public good and those in which the Nash equilibrium (equilibria) imply some positive (but possibly suboptimal) level and (2) simple voluntary provision versus contribution mechanisms based on more complex contribution facilitating mechanisms.

Zero Provision Environments and a Simple Contribution Mechanism

Consider the public-goods environment investigated by Marwell and Ames (1979, 1980, 1981) and by Isaac, Walker, and their colleagues (Isaac, Walker, and Thomas 1984; Isaac and Walker 1988a, 1988b, 1991). In this research, subjects are placed in an iterated game in which they must independently make an allocation of resources (tokens) between two types of goods. The first good (the private good) yields a fixed and known return per token to the subject making the allocation. The second good (the group good) yields a fixed and known return per token to the subject making the allocation, and to all other members of the group. This latter characteristic makes the group good a public good. Individual j receives value from the group good regardless of his or her decision to allocate tokens to the group good. We will refer to this simple decision situation as the voluntary contribution mechanism (VCM).

Isaac and Walker (1988b) investigate the simple case where the payoff function for the group good is continuous and the marginal value of a token placed in the group good is constant. For example, for one parameterization with group size equal to four, each subject receives a return of \$.01 for each token allocated to the private account. The group account pays, however, \$.003 per token to each member of the group for each token allocated by any member into the group account. The social dilemma is clear. In a one-shot game, the dominant strategy is for each subject to place all tokens into the private account (no provision of the public good). In a finitely repeated game, this is the unique complete information Nash equilibrium. The *group optimum* occurs, however, if each subject places all tokens into the group account.

Isaac and Walker examine behavior in a finitely repeated game where the end point is explicitly stated. A principal focus of their research is examining the impact of varying group size given the standard conjecture that larger groups have a more difficult task in providing public goods. A natural question is: Why should free riding increase in severity as the group size is increased? A logical response is that as the size of the group increases, the marginal return to each individual of another unit of the group good declines (due to crowding). Alternatively, public goods provided in large group settings may be characterized naturally by "small" marginal returns. These are both explanations that depend on a smaller marginal benefit from the public good with increases in group size. Is there, however, a "pure numbers" effect that influences the efficiency of public-goods provision? Defining the marginal return from the group good relative to the private good as the marginal per capita return (MPCR), Isaac and Walker investigate this question for MPCR values of \$.003/\$.01 = .30 and \$.0075/\$.01 = .75.

In a framework where the marginal payoff from the group good is constant (the aggregate payoff from the group good increases linearly), Isaac and Walker examine a pure numbers effect by varying the group payoff function so that the MPCR remains constant as N increases from 4 to 10. Alternatively, their design allows for the examination of group size effects based on crowding or an inherently small MPCR by allowing the MPCR to vary with group size. The findings can be summarized along three lines.

1. They observed greater provision of the group (public) good than predicted by the complete information noncooperative Nash model. Under some parametric conditions, provision reached over 50 percent of optimum, while in others, the rate of provision was less than 10 percent.
2. Provision declined with iteration of the game, but did not reach the predicted equilibrium.
3. A higher MPCR led systematically to less free riding and thus greater efficiency in the provision of the public good. No statistical support was found for a pure numbers effect. In fact, to the extent that there was any qualitative difference in the data, it was in the direction of the groups of size 10 providing larger levels of the public good than the groups of size 4. These results can be interpreted, however, as support for a crowding effect; larger groups exhibited more free riding if increases in group size generated a smaller MPCR.

The robustness of the Isaac and Walker results have been examined in depth in their work with Arlington Williams. Isaac, Walker, and Williams (1993) develop an alternative experimental methodology to circumvent the physical laboratory and budget constraints that make large group experiments generally infeasible. They use this methodology to examine the VCM environment with group sizes ranging in size from N = 4 to N = 100. The experiments presented employ two important procedural modifications relative to the research by Isaac and Walker: (1) decision-making rounds last several days rather than a few minutes and (2) rewards are based on extra-credit points rather than cash. These new experiments reported by Isaac, Walker, and Williams (and substantiated with further experimentation using cash rewards) led to several interesting findings. The results of initial extra-credit, multiple-session baseline experiments with groups of size 4 and 10 were consistent with the (cash, single-session) experimental results reported by Isaac and Walker. But Isaac, Walker, and Williams's experiments with groups of size 40 and 100 (using either extra-credit or cash rewards) led to several surprising results.

First, the impact from variations in the magnitude of the marginal per capita return from the public good (MPCR) appeared to vanish over the range (0.30, 0.75). Second, with an MPCR of .30, groups of size 40 and 100 provided the public good at higher levels of efficiency than groups of size 4 and 10. Third, with an MPCR of .75, there was no significant difference in efficiency due to group size. Further, experiments with N = 40 and a very low MPCR of .03 yielded the low efficiency levels previously observed with small groups and an MPCR of .30. The existence of an MPCR effect was thus reconfirmed for large groups. This research reveals that behavior in the VCM decision environment is influenced by a subtle interaction between group size and the value of the group good rather than simply the sheer magnitude of either. Experiments using both additional payoff information, more experienced subjects, and as many as 60 decision rounds provided further evidence that the public-good provision levels reported by Isaac and Walker and Isaac, Walker, and Williams could not be explained by simple conjectures of learning or insufficient iterations of the game.

Discrete Public Goods and VCM

The work described above sets the stage for an investigation of behavior in alternative experimental environments in which free riding is not a simple strategy of zero contributions to the public good. One direct way of changing the decision environment is to investigate the provision of public goods that are discrete (provision point or step function public goods; see chap. 3, fig. 3.5). Such experimental situations have naturally occurring counterparts in action situations in which a minimum level of provision support is necessary for productive services (a bridge for example).

For illustrative purposes, consider the design described above with an MPCR = .30 and N = 4. Isaac, Schmidtz, and Walker (1989) examined this environment, but with the following change. If allocations to the group account did not meet a specified minimum threshold, there was no provision of the public good and all allocations were lost (had a zero value). Isaac, Schmidtz, and Walker examined several designs in which they varied the minimum threshold. This type of decision situation created the "assurance problem" discussed in chapter 3. Zero contributions to the group good is no longer a dominant strategy nor the unique Nash strategy. Players have an incentive to contribute to the public good if they have some expectation (an assurance) that others will contribute. On the other hand, if others will provide the public good, the individual has an incentive to free ride on their contributions.

In a decision situation that combined the VCM mechanism with a provision point structure, Isaac, Schmidtz, and Walker found (1) in designs with provision points that require relatively low levels of contributions, numerous experimental groups were able, in early decision rounds, to overcome the assurance problem and provide the public good; (2) in experiments with higher provision points and in later decision rounds of most experiments, free-riding behavior tended to increase with resulting low levels of efficiency. These results are similar to results from a closely related provision point environment discussed by van de Kragt, Orbell, and Dawes 1983. In this study (where subjects made a binary decision to contribute or not to contribute to a group good), groups met the provision point in less than 35 percent of the decision trials.

Discrete Public Goods and Alternative Contribution Mechanisms

In anticipation that the specific rules of the contribution mechanism might significantly affect decision behavior, several studies have examined the provision point decision environment using an alternative contribution mechanism. For example, Dawes, Orbell, and van de Kragt 1984, Isaac, Schmidtz, and Walker 1989, and Bagnoli and McKee 1991 investigate several versions of what is commonly referred to as the "payback" mechanism. (See Palfrey and Rosenthal 1984 for a discussion of the strategic equilibria in provision point games with and without the payback mechanism.)

Specifically, contributions are made toward the provision of the public good. If the contributions do not meet the specified minimum, all contributions are returned to players making the contributions. As one might expect, this simple change can significantly affect decision incentives and observed behavior. Certainly the risks involved in making contributions are reduced. On the other hand, there is still an incentive to free ride if others will provide the public good.

The three studies cited above examine the payback mechanism in provision point environments that differ in several respects. However, even with the specific differences, the variation in findings is quite interesting. In one-shot decisions (with no value for contributions above the provision point and binary decisions to contribute or not to contribute), Dawes, Orbell, and van de Kragt (1984) found no significant effects on levels of contributions when comparing provision point experiments with and without the payback mechanism. On the other hand (in a decision environment in which contributions above the provision point have a positive value and subjects make nonbinary choices), Isaac, Schmidtz, and Walker found using the payback mechanism substantially increased efficiency in environments with higher provision points and to a lesser extent in the low provision point environment. They still observed significant problems in low and medium provision point environments (especially later decision periods) due to what they refer to as "cheap" riding. Significant numbers of subjects attempted to provide a smaller share of the public good than their counterparts, in some cases leading to a failure to meet the provision point. Finally (in a decision environment in which contributions above the provision point have no value and subjects make nonbinary decisions), Bagnoli and McKee (1991) found very strong results regarding the cooperative facilitating features of the payback institution. In their experiments, the public good was provided in 85 of 98 possible cases. Further, there was very little loss in efficiency due to overinvestments.[19]

Appendix 5.2.
Experimental Numbers

Experiment Number in Book	*Actual Experiment Number*
1	31
2	36
3	38
4	35
5	39
6	40

(continued)

19. For the reader interested in more detail, a sampling of other studies related to public goods provision includes Andreoni 1988; Brookshire, Coursey, and Redington 1989; Dorsey 1992; Isaac, McCue, and Plott 1985; Kim and Walker 1984; J. Miller and Andreoni 1991; Palfrey and Rosenthal 1992; and Sell and Wilson 1991; Ledyard 1993.

APPENDIX 5.2.—*Continued*

Experiment Number in Book	*Actual Experiment Number*
7	42
8	46
9	47
10	54
11	55
12	63
13	64
14	66
15	67
16	73
17	74
18	76
19	103
20	104
21	107
22	18
23	20
24	24
25	25
26	58
27	115
28	118
29	119
30	121
31	123
32	10
33	11
34	17
35	26
36	27
37	28
38	52
39	53
40	56
41	77
42	78
43	79
44	83
45	84
46	92
47	93
48	94
49	134
50	137

(continued)

APPENDIX 5.2.—*Continued*

Experiment Number in Book	*Actual Experiment Number*
51	138
52	57
53	80
54	85
55	86
56	95
57	96

APPENDIX 5.3. Market 2 Group Investment Decisions

	10-Token Parameterization			25-Token Parameterization		
Round	1	2	3	4	5	6
1	62	57	55	73	115	88
2	68	59	57	94	42	87
3	70	60	62	72	78	73
4	62	65	54	54	69	74
5	66	53	59	55	84	74
6	62	61	63	90	80	66
7	72	60	56	61	85	70
8	71	65	65	58	92	69
9	72	64	71	74	73	78
10	65	62	62	79	51	60
11	68	56	53	57	78	58
12	68	63	63	76	66	58
13	74	63	64	56	93	77
14	63	70	66	71	69	61
15	72	64	63	80	65	63
16	73	60	64	65	70	65
17	66	60	70	70	64	62
18	59	64	64	60	64	59
19	71	59	64	60	74	60
20	64	63	68	78	63	64
21	64	61	63			
22	69	62	66			
23	66	68	62			
24	62	60	66			
25	65	62	70			
26	67	64	66			
27	68	58	64			
28	70	62	70			
29	73	68	66			
30	63	60	70			

CHAPTER 6

Probabilistic Destruction of the CPR

Although the dissipation of net yield in a CPR is a serious economic problem, even more urgent is the problem of the destruction of the resource. As discussed in chapter 1, many CPRs are fragile, and human exploitation can lead to destruction. The fishery resources we describe in chapter 11, the forest resources in chapter 12, and the groundwater basins in chapter 13, are all CPRs that are potentially subject to destruction through overappropriation. A more subtle example is the geothermal CPR discussed in chapter 1. The Geysers in northern California have been exploited since 1960. Although grave uncertainties surround the underground structure of this resource, it is known to be fed by groundwater. Due to expansion of electrical generating capacity, the safe yield of steam has been exceeded. The Geysers are rapidly drying up, and are almost certain to be destroyed by the end of the century (Kerr 1991). Similar considerations apply to global commons, such as the buildup of carbon dioxide in the earth's atmosphere. Trace levels of this gas do not affect life on earth. Current models of the atmosphere leave a wide zone of uncertainty as to what happens when carbon dioxide builds up in the atmosphere (Reilly et al. 1987). At some level, as on the planet Venus, the carbon dioxide concentration destroys the biosphere.[1]

A range of *safe yields* underlies each of these classes of CPRs. A natural regeneration process is present that implies a range of exploitation in which the probability of destruction is 0. When the safe yield is surpassed, the resource faces probabilistic destruction. Indeed, at high enough levels of economic activity, the resource is destroyed with certainty. The key question is the tradeoff between jeopardizing the life of the resource and earning income from it. It is the behavioral response of highly motivated decision makers to this dilemma that we focus on in this chapter. The experimental research discussed in chapter 5 concentrated on the investigation of stationary (time-independent) appropriation problems in limited access CPR environments. This chapter extends our earlier work by introducing a significant

1. This chapter relies extensively on J. Walker and Gardner 1992.